UNCLASSIFIED

AD NUMBER
AD282762
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Proprietary Information; MAR 1962. Other requests shall be referred to Rome Air Development Laboratory, Griffiss AFB, NY 13441-5700.**
AUTHORITY
RADC ltr dtd 18 Mar 1965

THIS PAGE IS UNCLASSIFIED

Microwave Laboratory

W. W. Hansen Laboratories of Physics

STANFORD UNIVERSITY

STANFORD, CALIFORNIA

RADC-TDR-62-157 March 1962

Semi-Annual Technical Note

"MULTIMEGAWATT BROADBAND MICROWAVE TUBES"

M. L. Report No. 903
Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

TECHNICAL NOTE
for
CONTRACT AF 30(602)-2575
Project No. 5573
Task No. 557303

Prepared
for
ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
GRIFFISS AIR FORCE BASE
NEW YORK

ASTIA NOTICE:

Requests for additional copies by Agencies of the Department of Defense, their contractors, and other Government agencies should be directed to the:

ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA

Department of Defense contractors must be established for ASTIA services or have their "need-to-know" certified by the cognizant military agency of their project or contract.

OTS NOTICE:

All other persons and organizations should apply to:

U. S. DEPARTMENT OF COMMERCE
OFFICE OF TECHNICAL SERVICES
WASHINGTON 25, D. C.

PATENT NOTICE:

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other persons or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

EXISTENCE OF PROPRIETARY INFORMATION NOTICE:

This document is furnished under U. S. Government Contract No. AF 30(602)-2575 and shall not be released outside the Government (except to foreign Governments subject to these same limitations) nor be disclosed, used, or duplicated for procurement or manufacturing purposes, except as otherwise authorized by said contract, without the permission of the Microwave Laboratory. This legend shall be marked on any reproduction thereof in whole or in part.

ABSTRACT

1. Long-Slot TWT

The major efforts during this period have been directed toward the design of a system which will selectively attenuate the upper (TM_{02}) passband of the long-slot TWT. In the propagating system, i.e., two coupled transmission systems, the selectivity of the attenuation is determined by both the slot resonant frequency and the cutoff frequency of the external attenuating waveguide.

2. Ten Megawatt Cloverleaf TWT

This project is presently inactive, pending the modification of the existing amplifier. The modification intended is that of replacing the present Brillouin flow electron gun with a convergent confined flow gun.

3. Tapered Structures

The final report on this project is in preparation.

4. Centipede TWT

The work during this period has been directed toward effective suppression of unwanted interacting modes and the development of a structure promising bandwidths of the order of 2:1. Some possible schemes for mode suppression were considered in the light of all the available data. A detailed investigation has been carried out of basic properties of the new structure, tentatively named "extended cavity structure."

An analysis using coupled-mode theory shows that by properly coupling an external waveguide to a periodic structure, it should be possible to couple out the various backward waves and reflections which produce oscillations when that periodic structure is used in a high-power traveling-wave tube. A coupled-mode analysis, along with the effect of the waveguide on oscillations, is presented. According to the theory, it will be possible to use a dielectric-loaded waveguide to couple near the π-point

of the operating passband and to materially affect the "pulse-edge" oscillations that appear there, while producing relatively little effect on the forward gain in the amplifier operating band. It is also possible to affect the "loop" passband oscillations, wither separately or simultaneously with the π-point oscillations.

5. Electron Stick

Two methods of eliminating oscillations attributed to the backward wave ($m = -1$) of the helix were investigated. In the first, an additional helix of attenuator (Karma) wire is wound on the outside of the glass envelope and the insertion loss is measured for different wire diameters and pitch. The second involves periodically loading the electron stick with attenuator rings of higher loss material.

6. Hollow Beam Guns

For this project, efforts have been mainly concerned with two main areas. One is the continuation of the work on a general method for obtaining solutions to the equations of space-charge limited flow. The other is the development of a high-precision method of calculating to be used as an alternate to the method of analytic continuation for obtaining gun designs. These two topics are discussed.

7. Extended-Interaction Klystrons

The agreement between measured and theoretical interaction impedance and R_{sh}/Q on the stub-supported meander line has been improved. An error in the previous interpretation of perturbation data was found and corrected. An Ash circuit was built and tested for comparison with the stub-supported meander line.

8. Nonperiodic Dielectric-Lined High-Power TWT

Uniform cylinders of isotropic dielectric will be tested in conjunction with the Electron Stick. The reasons for this are discussed.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

This is the first Semi-Annual Technical Note (and simultaneously quarterly memorandum report number two for this contract, for the period 1 December 1961 to 28 February 1962). At the present time there are eight projects active under this contract:

1. Long-Slot TWT
2. Ten Megawatt Cloverleaf TWT
3. Tapered Structures
4. Centipede TWT
5. Electron Stick
6. Hollow Beam Guns
7. Extended-Interaction Klystrons
8. Nonperiodic Dielectric-Lined High Power TWT

The project formerly titled "Periodic Circuit Measurement Techniques" is now complete and a Technical Note is being prepared.

This contract extends the work previously done under RADC Contract AF 30(602)-1844 (and reported in various reports under that contract), and also provides support for certain additional studies of tube components and related matters.

The Responsible Investigator for this contract is Professor Marvin Chodorow.

I. OBJECTIVE OF THE CONTRACT

The objective of this contract is to conduct theoretical and experimental investigations of microwave tubes with a view toward the development of tubes capable of at least 10 megawatts of peak power, average power approaching 50 kilowatts, bandwidths approaching 30 per cent, gains of 35 db, and efficiencies of 40 per cent.

II. SUMMARY AND ANALYSIS OF THE WORK

1. Long-Slot TWT (R. A. Craig,* C. C. Lo)

A. OBJECTIVE

The objective of this project is to investigate a circuit which is theoretically capable of giving larger bandwidths than any megawatt tube yet tested, perhaps as high as 20 per cent, and to improve its performance and stability characteristics. This circuit uses coupled cavities in which the coupling is done through circumferential slots resonant at a lower frequency than the cavity resonance.

B. PRESENT STATUS

The major efforts during this period have been directed toward the design of a system which will selectively attenuate the upper (TM_{02}) passband of the long-slot TWT. Selective attenuation in its idealized form will decrease the rf fields sufficiently to preclude the build-up of oscillations in the upper passband, but will not affect the rf fields on the circuit at frequencies in the amplification band. Since the higher passband oscillations occur near the π-mode cutoff, the system under investigation is designed to couple power out of the tube structure at frequencies near this mode and dissipate the power in a medium external to the rf circuit.

Several systems of coupling power from the slow-wave circuit to an external circuit which does not interact with the electron beam have been

---

*Project supervisor

considered in the past.[1] A simpler version consisting of individual coupling from each section of the slow-wave structure to a lossy cavity has been investigated in this program, in conjunction with the cloverleaf circuit. Cold-test measurements were made which indicated the feasibility of such a scheme, but tests in an actual amplifier were never conducted. The difficulty with the coupled transmission line scheme is that the propagation constants of the two systems must be nearly equal and the device must be sufficiently long to allow energy transfer from the tube to the waveguide of sufficient magnitude to preclude oscillations. If, however, the gain is greater than the loss, oscillations can still occur. Individual coupling, on the other hand, can always reduce the fields sufficiently to stop oscillations, provided that sufficient coupling to the lossy cavity can be obtained without adversely affecting the desired operating band.

The method of selective loading presently being considered to suppress TM_{02} passband oscillations in the long-slot structure is in reality a combination of the two aforementioned methods. If the attenuation of one transmission system is much higher than the attenuation in the other, little coupling can be obtained in a reasonable length of structure. However, if no propagation in the external system is assumed, then a resonant slot can be allowed to radiate directly into a resistive material designed to match the radiation resistance of the slot. The external "load" can be a simple waveguide heavily loaded with carbonized ceramic, for example. Care must be exercised so direct coupling between cavities through adjacent slots is minimized in order to maximally attenuate the entire system. The degree of coupling can be adjusted somewhat by increasing the number of radiating slots in each section of the rf structure. Obviously, the cutting of the slot in a cavity wall will affect the frequency of the cavity even though the slot is nonresonant, so in practice only a few slots (probably two) can be cut in the wall of the slow-wave circuit without seriously perturbing the propagation characteristic of all the TM modes.

---

[1] See, for example, N. Rynn, "On the Periodic Coupling of Propagating Systems," IRE Trans. on Electron Devices, ED-6, 325-329 (July 1959).

In the propagating system, i.e., two coupled transmission systems, the selectivity of the attenuation is determined by both the slot resonant frequency and the cutoff frequency of the external attenuating waveguide. In the system under investigation, the latter should not be important, but in the interests of compactness as well as insurance against the possibility of some propagation, dimensions identical to the propagating system will be used.

During the past interval, preliminary work has been performed to determine the properties of the various elements of the proposed attenuation in an effort to determine the optimum location of the slot in relation to the slow wave circuit. Minimizing the loading and perturbation in the operating passband must be obtained with nearly maximum loading in the higher passband, at least at frequencies where the tendency toward oscillation is the greatest. This work is now in process and no definitive results have been obtained as yet. Much effort has gone into obtaining good impedance matches to the slow-wave circuit at the oscillation frequencies so the total radiated power from the slot can be measured. Also, the slot resonant frequency must be determined experimentally since it does not have a simple dependence on the dimensions as in the case of a smooth waveguide, but also depends on slot location and the curvature and thickness of the wall of the slow-wave structure.

The next interval will be devoted to obtaining dimensions and attenuation values in a system designed to be as selective to mode attenuation as possible. It is planned to begin the construction of an amplifier as soon as the dimensions are available. Present intentions are to obtain wide bandwidth with stable operation at beam voltages consistent with optimum efficiency in the 2-3 megawatt range of power output.

2. Ten Megawatt Cloverleaf TWT (R. A. Craig*)

A. OBJECTIVE

The objective of this project is to develop a cloverleaf TWT with 10 megawatts peak power, a TWT with as high efficiency as possible and as much bandwidth that can be obtained in a cloverleaf circuit.

*Project supervisor

B. PRESENT STATUS

This project is presently inactive pending the modification of the existing amplifier. The modification intended is that of replacing the present Brillouin flow electron gun with a convergent confined flow gun.

3. Tapered Structures (R. A. Craig,* C. C. Lo)

A. OBJECTIVE

The objectives of this project are to demonstrate that the pulse edge oscillation problem in high-power TWT amplifiers can be reduced or eliminated completely by the use of a tapered output section. It is to be understood that the other uniform sections would be designed with low enough gains so that pulse edge oscillations would not exist in the sections and be transmitted to the output by the modulated electron beam.

B. PRESENT STATUS

The final report on this project is in preparation.

4. Centipede TWT (D. K. Winslow,* F. Ivanek, A. Bahr)

A. OBJECTIVE

The centipede structure has given, to date, the most all-around satisfactory circuit performance for a high-power traveling-wave tube. The objectives of the present study are (1) to suppress the observed oscillations in the higher frequency loop passband and also the pulse-edge oscillations at the π-mode of the operating band without incorporating excessive attenuation in the frequency range of operation, and (2) to improve the overall circuit performance. The first objective is being pursued using two alternative approaches: coupling of the unwanted modes into a heavily attenuated external region or waveguide by means of resonant slots, and selective mode coupling of the undesired modes to an external lossless uniform guide. The techniques used here could be adapted to other types of circuits, such as the "cloverleaf" or the "long-slot." The study directed toward the second objective, i.e., improved circuit performance, has a somewhat wider scope in that it also

*Project supervisors.

makes use of the existing knowledge of related structures and indicates the possibility of building new types of circuits.

B. PRESENT STATUS

The current work is reported in two parts. Part I presents the investigation of coupling of undesired modes into an external attenuated region or into a waveguide which has the waveguide cutoff frequency above the operating frequency range of the tube. The improvement of overall circuit performance is also included in this section. Part II has objectives similar to those of Part I and considers a similar method of coupling. The essential difference is that the external waveguide is coupled to the structure throughout the operating frequency range of the tube as well as the frequency ranges in which instabilities are observed. Attenuation of the undesired frequency ranges, with negligible attenuation in the operating band, is accomplished here by properly adjusting the phase and attenuation characteristics of the external circuit.

Part I

Work in the reported period was directed toward effective suppression of unwanted interacting modes and the development of a structure promising bandwidths of the order of 2:1.

The loop mode coupler experiment as described in the Third Annual Report[1] was repeated with the coupling slot height doubled to 1/4 inch in order to increase energy transfer from the loop mode into the rectangular secondary guide. The results of the tests are more inconsistent than the previously reported ones, for the coupling was more critically dependent on frequency and coupler length. On the average the coupling did not increase. The effect on the TM_{01} passband became more pronounced, bringing about a more severe passband splitting.

The nonselective alternative scheme of suppressing unwanted interacting modes about the TM_{01} passband was tested concurrently. A 16-section leaky wall structure was built with four symmetrically arranged slots in each section. The slot width was 1.375 in., approximately the same as in the loop mode coupler, its height 1/16 in. and the slot thickness 0.800 in.

---

[1]Third Annual Report for Contract AF 30(602)-1844, Microwave Laboratory Report No. 854, Stanford University, pp. 77-95 (February 1962).

The slotted structure was wrapped in a 3/4 in. layer of Eccosorb LS22 absorber. Resonant structure measurements showed practically negligible effects on the TM_{01} passband, but no loop mode resonance could be detected at all, suggesting that this unwanted mode is leaking out efficiently into the absorbing layer.

The above results called for a detailed study of coupling and leaking slots, especially in view of the inconsistent behavior of the loop mode coupler. To date, the following conclusions have been reached:

(1) The resonant frequency of the slot in the cylindrical ring supporting the loop system varies rapidly with various slot thicknesses. A one inch increase in slot thickness from 3/8 to 1-3/8 in., for example, caused a 800 Mc/s decrease in slot resonant frequency from 5500 to 4700 Mc/s, Mc/s, the calculated half-wavelength slot resonance being at 4500 Mc/s. Furthermore, slot coupling varies rapidly near the self resonances of the loop system.

(2) The amount of bandwidth of coupling through a slot of given width and height can be controlled by varying its thickness and/or the height of the secondary rectangular waveguide. An increase of slot thickness increases the amount but reduces the bandwidth of coupling, while a decrease of coupled waveguide height increases both the amount and bandwidth of coupling.

To avoid the undesired effects described under (1), it was decided to couple directly to the centipede "cavities" instead of coupling to the outer loop volume. This required a redesign of the centipede structure such that there is now at the cylindrical wall a 1/16 in. separation between the adjacent loop systems, the period length remaining unchanged. This reduction of the volume enclosed by the outer loops has only negligible effect on the TM_{01} passband, but the loop passband is shifted upwards due to the reduction in loop length. The 1/16 in. separation between the outer loops of the adjacent loop systems will be used for coupling or leaking slots whose properties will be examined. A major

anticipated advantage of this scheme over the previous one is the possibility of coupling to the TM_{01} mode at π phase shift per section.

Some possible schemes for mode suppression were considered in the light of all the available data. One attractive possibility would be to combine some of the features of the loop mode coupler and the leaky wall structure. Using a secondary waveguide heavily loaded with distributed loss and coupled to each section of the periodic structure, we would prevent directional coupler-type interaction and might achieve effective absorption of the TM_{01} π-mode and the loop mode, taking advantage of the waveguide cutoff properties to prevent absorption of the TM_{01} mode in the operating frequency range. One single or two different slot sizes come into consideration, depending upon the separation of the two frequency regions where tight coupling is desired. In some cases it might be advantageous to use separate waveguides for more effective mode suppression. A study of rectangular waveguides loaded with distributed loss will be undertaken next to obtain necessary data for the design of a centipede structure with suppressed unwanted interacting modes.

A detailed investigation has been carried out of basic properties of the new structure described in the previous report,[1] under the tentative name "extended cavity structure." It was found that the initially assumed field pattern does not lead to an adequate description of the structure behavior. The structure is rather a combination of two disk loaded structures, one with the outer disks alone and the other with the inner disks alone. The dispersion characteristics and relative interaction impedances of both basic structures, i.e., the structure with the inner disks only and the one with the outer disks only, and of the combined structure were measured for different common diameters of the inner disks and the outer disk apertures. The figure on p. 6 of the previous report is referred to where this diameter is 2.500 in. The smallest diameter used was 2.000 in., the largest was 3.250 in. As this diameter is increased, the TM_{01} passband of the outer disk structure increases while that of the inner disk structure decreases. The TM_{01} passband of the combined structure is in all cases slightly smaller than the narrower one of the two basic structures for the particular common diameter. Optimum conditions

---

[1]Quarterly Memorandum No. 1 for Contract AF 30(602)-2575, Microwave Laboratory Report No. 881, Stanford University, pp. 5-6 (January, 1962).

for both bandwidth and interaction impedance of the combined structure are obtained when the basic structures have approximately equal bandwidths. With a common diameter of 3.000 in., a 2255 Mc/s wide TM_{01} passband extending from 2402 to 4657 Mc/s was obtained. Several possible methods of supporting the inner disks in a practical structure were examined. Satisfactory performance was obtained, so far, only with radial metallic strips extending to the cylindrical structure wall. In this particular case we are dealing essentially with the modified long-slot structure having complete rings instead of fins.[2]

The described structure might be suitable for combining positive and negative mutual magnetic coupling. This was first attempted by Allen[3] but his particular arrangement had a limited overall bandwidth due to the accommodation of coupling slots and loops in the same region of the structure. If we would use the inner plates of the combined disk structure to accommodate the S-shaped loops, there would be two completely separated regions for the two types of coupling. By extending the TM_{01} passband at its lower end, bandwidths of 2:1 or better are likely to be obtained.

---

[2] M. A. Allen, "Coupling of Multiple-Cavity Systems," Microwave Laboratory Report No. 584, Stanford University, p. 120 (April 1959).

[3] <u>Ibid</u>., pp. 121-126.

Part II

An analysis using coupled-mode theory[1,2] shows that by properly coupling an external waveguide to a periodic structure, it should be possible to couple out the various backward waves and reflections which produce oscillations when that periodic structure is used in a high-power traveling-wave tube. The theory shows the synchronism of phase velocities is a prime requisite for large transfer of power between coupled modes. By loading the external waveguide with dielectric and by adjusting the cutoff frequency, one can cause the ω-β characteristic of the waveguide to intersect at the proper places with the ω-β characteristic of the periodic structure. Coupling near the π-point of the operating passband is desired since this is where the "pulse edge" oscillations occur. Also, it is desirable to couple simultaneously to any other passbands which will produce oscillations when the tube is operating at a voltage that will synchronize with that mode. The proper waveguide characteristic in relation to the centipede structure is shown in Fig. 1. Since, by their very nature, all of the space harmonics are in phase with each other periodically (the period of phase-synchronism being that of the structure) and since, physically, one is limited to one coupling mechanism per section of periodic structure, phase-synchronism with one space harmonic implies phase-synchronism with all space harmonics.

The utility of this oscillation suppression scheme will depend not only on how well it suppresses oscillations, but also on how little it degrades the gain of the tube in the operating frequency range. Reference to Fig. 1 shows that in the operating frequency range there is a large phase-difference between the waveguide mode and fundamental space harmonic of the structure. Therefore, from coupled-mode theory one knows that the waveguide will not have a great effect on the gain in this frequency range. Furthermore, even if the waveguide mode and fundamental space harmonic are synchronous, the effect on gain will be relatively small.

---

[1] S. E. Miller, "Coupled Wave Theory and Waveguide Applications," B.S.T.J. 33, 661-719 (May 1954).

[2] W. H. Louisell, "Coupled Mode and Parametric Electronics," John Wiley and Sons, Inc. (1960).

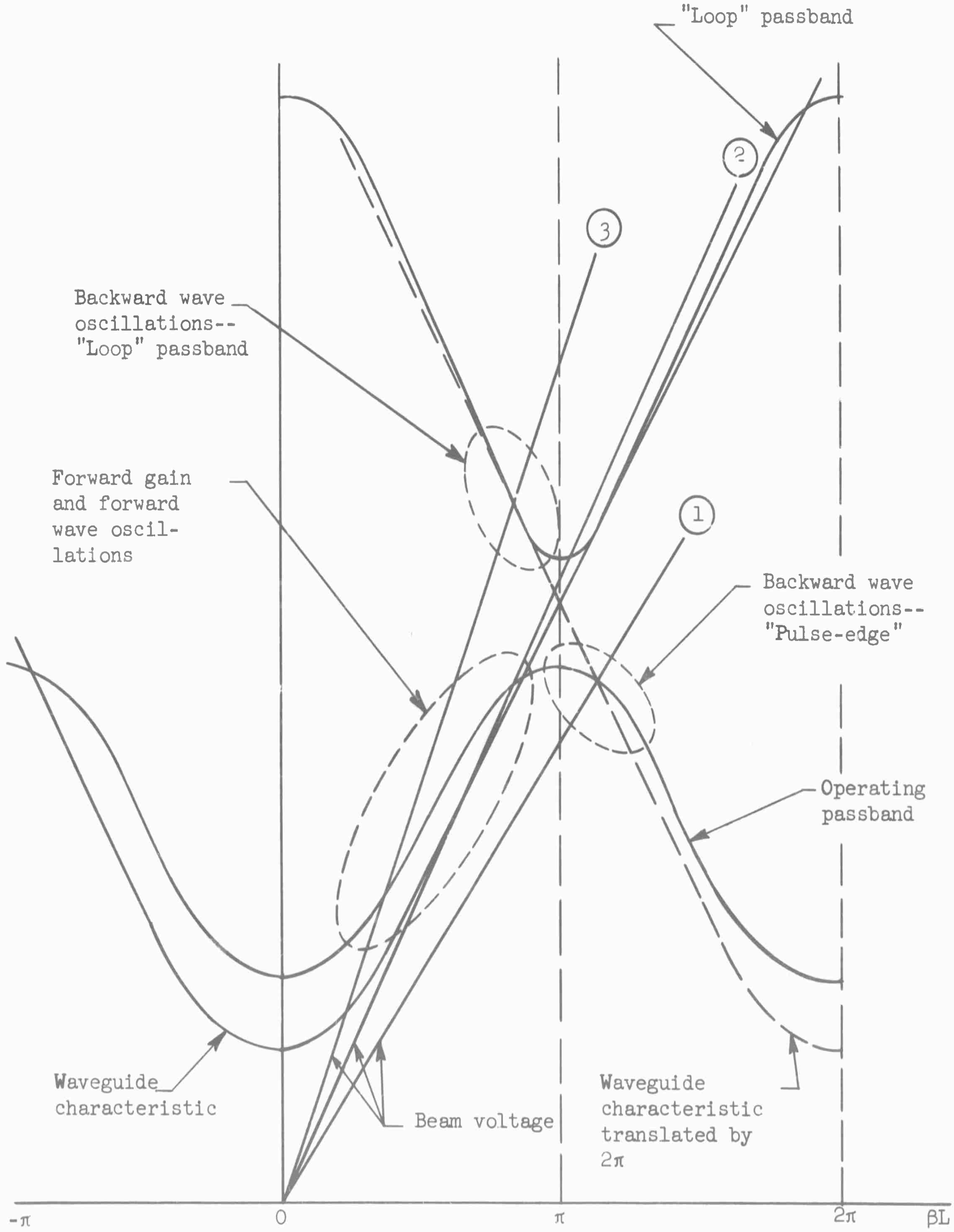

FIG. 1--Dispersion characteristics of centipede structure and dielectric-loaded waveguide.

A coupled-mode analysis which gives this last result, along with the effect of the waveguide on oscillations, is presented in the next section.

Coupled-Mode Analysis

(a) General Considerations and Assumptions:

In order to apply coupled-mode theory to a coupled system consisting of a beam, circuit, and waveguide and to obtain a system of equations which are tractable, one must make a number of simplifying assumptions. These assumptions are:

1. The coupling is weak.
2. The coupling is continuous.
3. Coupling to reflected waveguide and circuit modes may be neglected.
4. Coupling to the fast space-charge mode may be neglected.

Some discussion of these assumptions is in order.

The coupling between all modes must be small because the coupled-mode type of analysis is a perturbation analysis. The coupling between the beam and circuit was estimated from the asymptotic gain obtained with an actual tube (about 1.8 db per section) and was found to cores-pond to a Q for the coupled modes of about 25. It is not clear from the theory what the limiting Q should be, but it is reasonable to assume that coupled-mode theory used for a system with this magnitude of coupling will give meaningful physical results.

On the basis of the weak coupling assumption, the coupling was assumed to be a continuous function of distance, whereas in reality it is discrete. Sample calculations show that, when calculating the power transferred between two modes, the differences between the results of the discrete and continuous theory are small as long as the coupling per unit length is "small." The degree of "smallness" required is clear from the sample calculations and is consistent with the values of coupling estimated from typical values of gain.

Neglecting reflected waveguide and circuit modes is a good assumption for continuous, weak coupling because, under these conditions, the directly coupled reflected waves have all phases with respect to any given point and so tend to cancel out on the average. However, because the coupling

is actually discrete, the reflected waves generated at each coupling hole will have certain definite phase relationships with respect to each other and so, in general, they will not cancel. Hence, it is assumed that the coupling mechanism is directive, i.e., it does not generate reflected waves.

For typical values of C and QC, neglecting the coupling to the fast space-charge mode is a reasonable assumption because then there is enough phase velocity separation between the fast and slow space-charge modes so that for synchronism to the slow space-charge mode there is relatively little coupling to the fast space-charge mode. One focuses attention on the slow space-charge mode because this is the beam mode which causes the tube to exhibit gain and/or to oscillate.

After making all of these assumptions, one finds that the minimum number of modes which must be retained are three:

1. the forward "equivalent" mode on the periodic structure (or backward "equivalent" mode if one is interested in backward wave oscillations),

2. the forward mode of the waveguide (or backward mode), and

3. the slow space-charge mode of the beam.

(b) General Three-Coupled-Mode Analysis:

The mode amplitudes are designated by E_i, where $|E_i|^2$ is the power carried in that mode. The modes are numbered in the manner indicated in Fig. 2.

The differential equations which describe the coupled system are

$$-\frac{d}{dz}\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = j\begin{bmatrix} \beta_1 & \mp d_{12} & \mp d_{13} \\ d_{12} & \beta_2 & 0 \\ \mp d_{13} & 0 & \beta_3 \end{bmatrix}\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}. \qquad (1)$$

Here β_i is the propagation constant for the i^{th} mode and d_{ij} is the coupling/unit length between the i^{th} and j^{th} modes. For typical

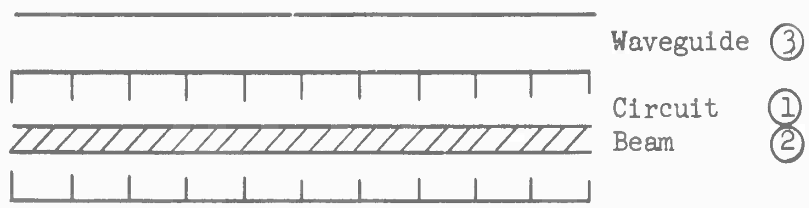

FIG. 2--Basic coupled structure.

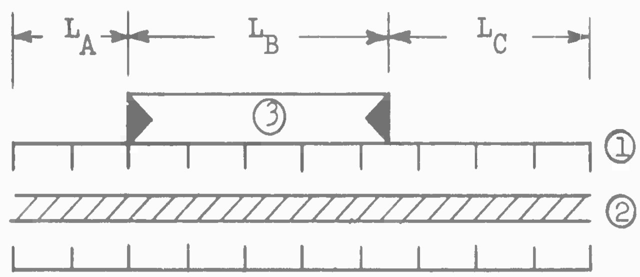

FIG. 3--Coupled structure used in analysis of nonreciprocal attenuator and backward wave oscillator.

values of asymptotic gain (1.8 db/section) d_{12} is about 0.125 cm^{-1} for forward wave interaction and about 0.085 cm^{-1} for backward wave interaction. The top sign corresponds to energy flow in modes 1 and 2 in opposite directions and the bottom sign corresponds to energy flow in modes 1 and 2 being in the same direction. Thus, the top sign corresponds to a case where traveling-wave gain would be obtained, and the bottom sign corresponds to a case where backward wave oscillations could occur.

In general, the new normal modes for the coupled-system are obtained by diagonalizing the matrix in Eq. (1) and then using a linear combination of these normal modes to satisfy any particular set of boundary conditions that may be desired. Since, under the assumptions of coupled-mode theory $|E_1|^2$ represents the power in the physical part of the system designated by "1" both before and after the parts of the system are coupled, one can then calculate the power flow in any part of the system (to first order).

As an example, consider the system shown in Fig. 2, where the external waveguide extends the whole length of the periodic structure. First, consider the case where modes 1 and 2 have energy flows in opposite directions. Since the group velocities of all the modes are in the same direction, all the boundary conditions can be applied at one end of the tube, i.e.,

$$\begin{bmatrix} E_1(0) \\ E_2(0) \\ E_3(0) \end{bmatrix} = \begin{bmatrix} C_1^F \\ C_2^F \\ C_3^F \end{bmatrix} = \begin{bmatrix} \propto \text{Power injected on circuit} \\ \propto \text{Modulation injected on beam} \\ \propto \text{Power injected into waveguide} \end{bmatrix} . \tag{2}$$

Assuming that the uncoupled modes are synchronous $(\beta_1 = \beta_2 = \beta_3 = \beta)$, the solutions of Eq. (1) subject to these boundary conditions are

$$E_1(z)\, e^{j\beta z} = j\, \frac{C_2^F + \sqrt{D}\, C_3^F}{\sqrt{D - 1}} \sin K_z^- + C_1^F \cos K_z^- \tag{3a}$$

and

$$E_2(z)\, e^{j\beta z} = \frac{\sqrt{D}\, C_3^F + D C_2^F}{D - 1} + \frac{C_2^F + \sqrt{D}\, C_3^F}{1 - D} \cos K_z^- - j \frac{C_1^F}{\sqrt{D - 1}} \sin K_z^- \qquad (3b)$$

$$E_3(z)\, e^{j\beta z} = \frac{C_3^F + \sqrt{D}\, C_2^F}{1 - D} + \frac{\sqrt{D}\, C_2^F + D C_3^F}{D - 1} \cos K_z^- + j \frac{\sqrt{D}\, C_1^F}{\sqrt{D - 1}} \sin K_z^- \quad , \qquad (3c)$$

where

$$D = \frac{d_{13}^{\,2}}{d_{12}^{\,2}} \text{ and } K^- = \sqrt{d_{13}^{\,2} - d_{12}^{\,2}} \quad .$$

From Eqs. (3) one sees that:

(1) Whether a growing wave occurs or not depends entirely on whether or not the coupling from the circuit to the beam is stronger than the coupling from the circuit to the waveguide. If a growing wave exists, then complete power transfer between the circuit and waveguide is not possible, and the rate of growth of the growing wave is reduced by the presence of the waveguide.

(2) If the coupling from the circuit to the waveguide is stronger than to the beam, then complete power transfer between the waveguide and circuit is possible, but it takes a greater coupling length than when no beam is present.

When the waveguide and circuit modes are nonsynchronous, the effect of the waveguide on the TWT becomes smaller as the departure from synchronism becomes larger.

Secondly, consider the case where modes 1 and 2 have energy flows in the same direction. The boundary conditions become

$$\begin{bmatrix} E_1(\ell) \\ E_2(0) \\ E_3(\ell) \end{bmatrix} = \begin{bmatrix} C_1^B \\ C_2^B \\ C_3^B \end{bmatrix} = \begin{bmatrix} \propto \text{Power injected on circuit} \\ \propto \text{Modulation injected on beam} \\ \propto \text{Power injected into waveguide} \end{bmatrix} , \qquad (4)$$

where ℓ is the length of the coupled structure. The solutions (assuming $\beta_1 = \beta_2 = \beta_3 = \beta$) are

$$E_1(z)\, e^{j\beta z} = j\sqrt{1 + D}\; S_{23} \;\sin K^+(\ell - z) + \sqrt{1 + D}\;\; S_1 \left[\cos K^+(\ell - z) + \frac{1}{D} \cos K^+_z\right] \tag{5a}$$

$$\begin{aligned} E_2(z)\, e^{j\beta z} = C_2^B &+ S_{23} \left[\cos K^+(\ell - z) - \cos K^+\ell\right] \\ &+ jS_1 \left[\sin K^+(\ell - z) - \frac{1}{D} \sin K^+_z - \sin K^+\ell\right] \end{aligned} \tag{5b}$$

$$\begin{aligned} E_3(z)\, e^{j\beta z} = -\frac{1}{\sqrt{D}}\; C_2^B &+ \sqrt{D}\;\; S_{23} \left[\cos K^+(\ell - z) + \frac{1}{D} \cos K^+\ell\right] \\ &+ j\sqrt{D}\;\; S_1 \left[\sin K^+(\ell - z) - \frac{1}{D} \sin K^+_z + \frac{1}{D} \sin K^+\ell\right] \quad , \end{aligned} \tag{5c}$$

where $K^+ = \sqrt{d_{12}^{\;2} + d_{13}^{\;2}}$ and

$$S_1 = \frac{C_1^B}{\cos K\ell + D} \frac{D}{\sqrt{1 + D}}\, e^{j\beta\ell}$$

$$S_{23} = \frac{C_2^\beta + \sqrt{D}\; C_3^B\, e^{\,j\beta\ell}}{\cos K\ell + D} \quad .$$

To find the start-oscillation length for backward wave oscillations, one looks for poles in the expression for $|E_1(0)|^2$. For the special case $C_1^B = 1$, $C_2^B = 0$, $C_3^B = 0$, one has

$$|E_1(0)|^2 = \left[\frac{1 + D \cos K^+\ell}{D + \cos K^+\ell}\right]^2 \quad . \tag{6}$$

From this espression one sees that there can be no oscillations if the coupling between the circuit and waveguide is greater than the coupling between the circuit and the beam.

In an actual situation one must consider an external waveguide which is not coupled to the tube along the entire length of the tube. Thus, the effect of the external waveguide on the behavior of the tube will depend on its position with respect to the ends of the tube. An analysis of this situation is presented in the next two sections.

(c) Nonreciprocal Attenuator:

Forward-wave oscillations are caused in a traveling-wave tube when, due to mismatches at the input and output couplers of the tube, waves reflected at the output reach the input, are reflected again and re-interact with the beam. Thus, due to these reflections, a feedback path is set up and if the net loop gain exceeds one, oscillations will occur. It is therefore desirable to have an attenuator which does not materially affect the gain in the forward direction but which severely attenuates the reflected waves. In an ideal situation an external waveguide coupler will do this because of its phase discrimination characteristics.

In Fig. 1 consider the case when the beam voltage is at position 2. At the intersection of the beam voltage line and fundamental space harmonic there is the possibility of strong interaction between the beam and circuit. Hence, there can be gain and also forward-wave oscillations in this region. Note that all the power reflected at the output coupler is brought back in the space harmonics with negative group velocity (by definition, the forward fundamental is said to have positive group velocity). However, these space harmonics are out of synchronism with the beam and, hence, do not interact appreciably with it. These backward space harmonics do interact with the waveguide mode, as explained in the introduction. Since there are only two modes interacting in the backward direction, all the reflected power can be coupled out and there will be infinite attenuation for the reflected waves. Since the coupling to the beam is known, the condition of complete reflected power transfer to the external guide determines the coupling to the waveguide and the effect of the waveguide on the forward gain can be calculated.

The physical setup of the situation to be analyzed is shown in Fig. 3. This problam can be solved by finding the modes in each part of the structure (A, B, and C) and, assuming no reflections at the interfaces, by matching the solutions across the boundaries. The circuit mode found by this method (for complete synchronism) is

$$E_1(LT)\, e^{j\beta L_T} = \cosh x\, L_B \cosh d_{12}(L_A + LC)$$
$$+ \frac{1}{\sqrt{1 - D}} \sinh x\, L_B \sinh d_{12}\, (L_A + L_C) \tag{7}$$
$$+ D \frac{\sinh^2 \frac{xL_B}{2}}{1 - D} \left\{ \cosh d_{12}(L_A + L_C) - \cosh d_{12}\, (L_A - L_C) \right\} ,$$

where

$$L_T = L_A + L_B + L_C \quad ,$$

and

$$x = \sqrt{d_{12}^{\,2} - d_{13}^{\,2}} \quad .$$

Given L_B , then $L_A + L_C$ is equal to a constant. Therefore, it follows that $E_1(L_T)$ has a maximum when $L_A = L_C$, i.e., the best position of the coupler is in the middle of the tube. (Remember, however, that this is a small-signal analysis.)

Using 0.125 cm^{-1} for the beam-circuit coupling d_{12} , it was found that the asymptotic gain of the TWT was reduced by 0.25 to 0.15 db/section for reasonable coupler lengths and optimum coupler position. Thus, a tube which is 20 sections long and which originally has an overall gain of 30 db will have an overall gain of 26 db when a coupler is added. It is to be noted that the actual reduction in gain at the center of the band of operation of the tube will be <u>less</u> than that quoted above because in the center ' the operation band the waveguide mode is out of synchronism with the circuit and beam modes.

(d) Backward Wave Oscillations:

In Fig. 1 consider either beam voltage 1 or 3 . In either case, backward wave oscillations can occur. For beam voltage 1 they appear as "pulse edge" oscillations on the rise and fall of the beam voltage pulse and for beam voltage 3 they appear on the top of the beam voltage pulse. These two regions of interaction are indicated in Fig. 1. The waveguide mode can interact with the circuit mode in both of these regions, as explained in the introduction. Hence, it is of great interest to calculate the effect of the external waveguide coupling on the start-oscillation length. (The length rather than current is chosen as a parameter because it is assumed that the beam-circuit coupling is fixed.)

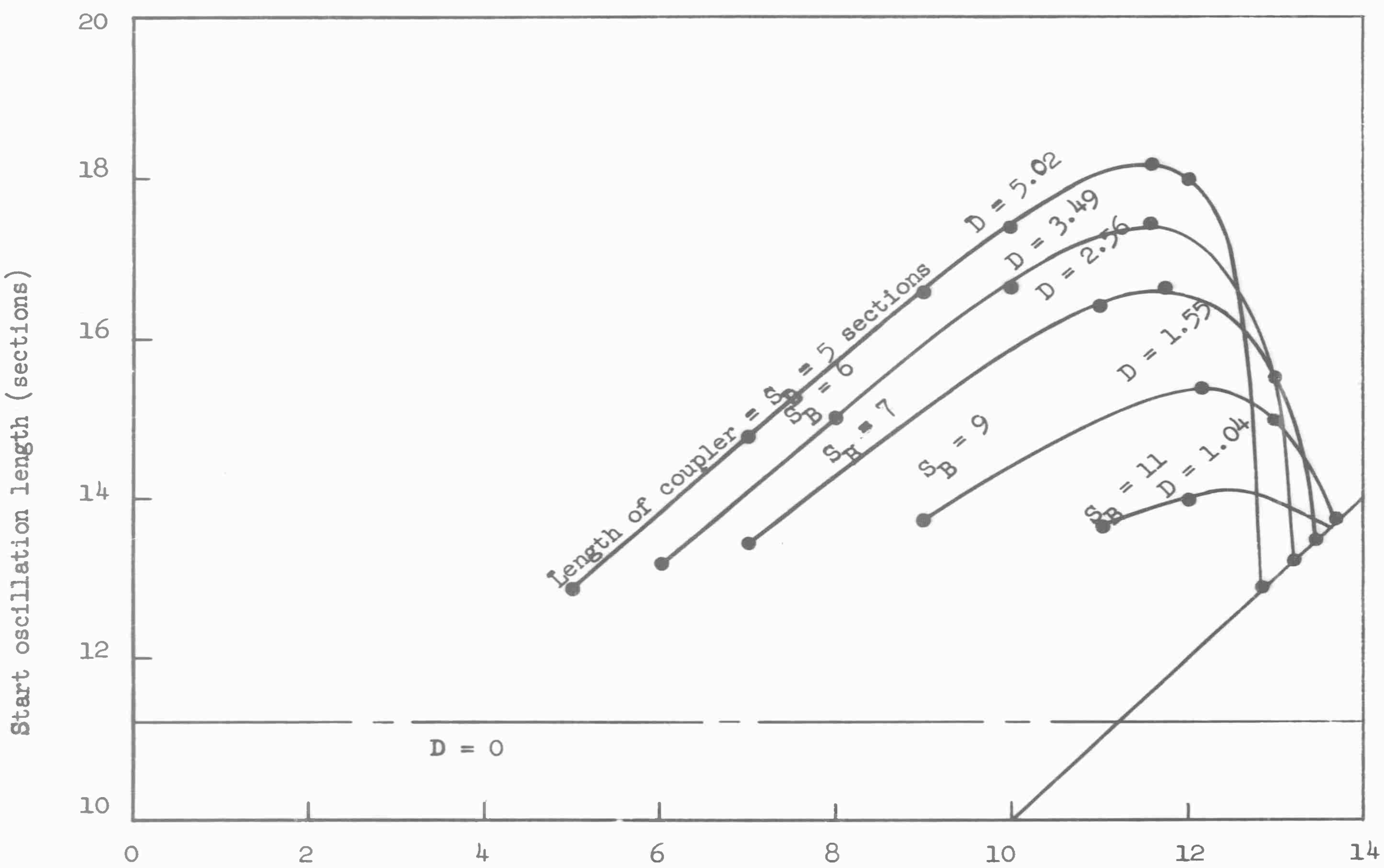

FIG. 4--Start oscillation length vs coupler position for complete reflected power transfer to the external guide.

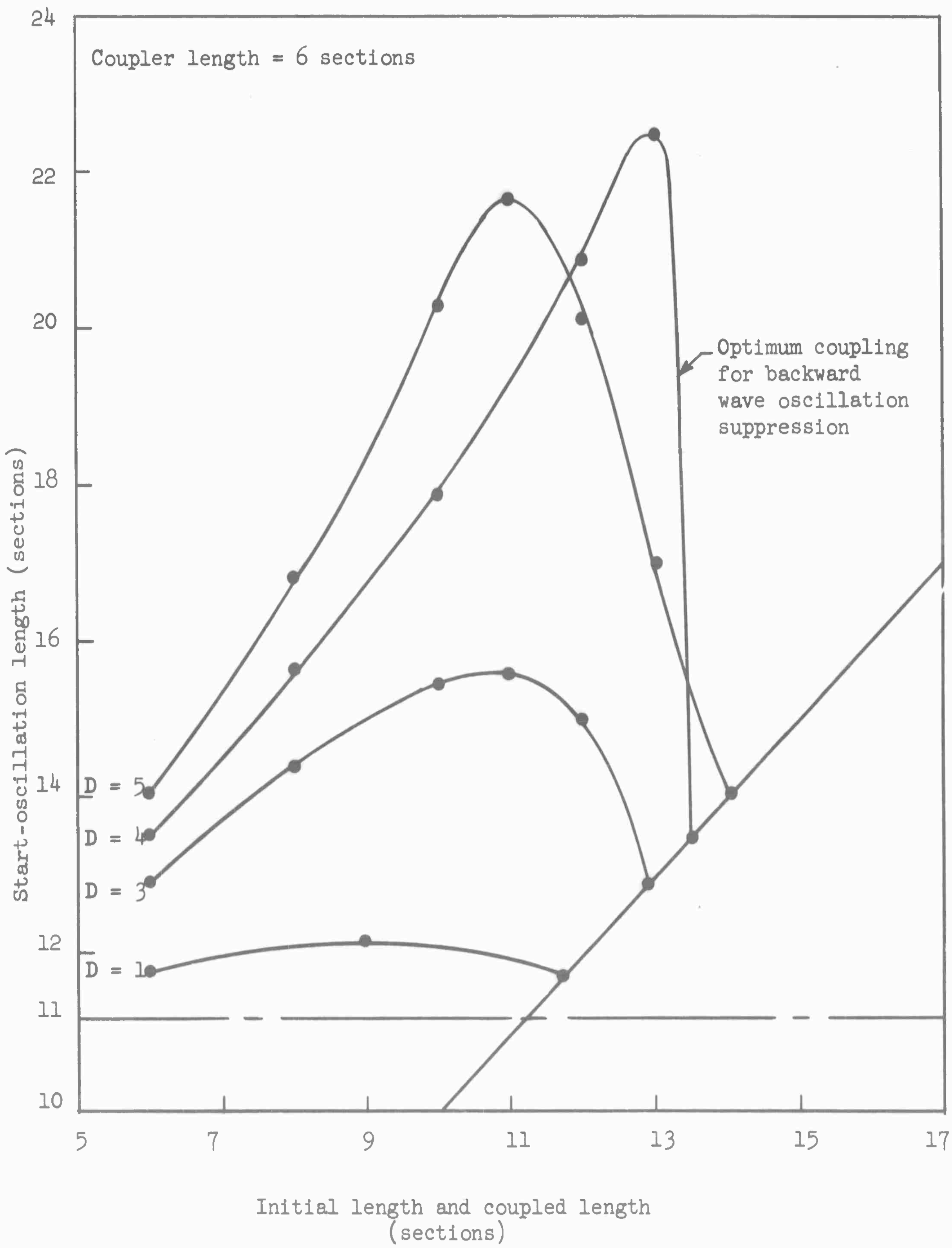

FIG. 5--Start oscillation length vs coupler position for various couplings to the external guide.

The physical setup to be analyzed is again that shown in Fig. 3. The same techniques can be used that were used in calculating the gain, i.e., matching solutions across the regions containing external coupling and those containing no external coupling. The boundary conditions are that $E_1(L_T) = 1$, $E_2(0) = 0$, and $E_3(L_A + L_B) = 0$. The start-oscillation length is found from the condition that $E_1(0)^2$ have a pole. Accordingly, the equation for the start-oscillation length L_{TO} was found (for complete synchronism) to be

$$\sqrt{1 + D} \sin \Theta_B \sin (\Theta_A + \Theta_C) - \cos(\Theta_A + \Theta_C) \left[\cos \Theta_B + \frac{D}{2}(\cos \Theta_B + 1)\right] + \cos(\Theta_A - \Theta_C)\frac{D}{2} (\cos \Theta_B - 1) = 0 \quad , \qquad (8)$$

where

$$\Theta_A = d_{12} L_A, \; \Theta_B = K^+ L_B, \Theta_C = d_{12} L_C \quad .$$

Given Θ_A and Θ_B , one finds Θ_{CO} from Eq. (8) and then uses

$$L_{TO} + L_A + L_B + L_{CO} \quad . \qquad (9)$$

The start-oscillation length is plotted vs coupler position in Figs. 4 and 5. Figure 4 shows the case when the circuit-waveguide coupling is determined by the condition that all the reflected power be coupled out when there is no interaction with the beam (e.g., when the beam voltage is in position 2 or 3). Figure 5 shows the case when the start-oscillation length is optimized with respect to circuit-waveguide coupling for a given coupler length. The most outstanding feature of these curves is the fact that the start-oscillation length has a sharply peaked maximum as a function of coupler position. The increase in start-oscillation length can be quite substantial.

It is to be noted that the circuit-waveguide coupling which corresponds to the maximum start-oscillation length does not correspond to complete power transfer when no beam is present. The reason for this is the fact that a beam <u>is</u> present in the backward-wave oscillation analysis; the coupling giving a maximum start-oscillation length is that corresponding to maximum power transfer when a beam <u>is</u> present. The difference between the optimum circuit-waveguide coupling for beam present and no beam present is small when that coupling is large.

Conclusions and Future Plans

According to the theory, it will be possible to use a dielectric-loaded waveguide to couple near the π-point of the operating passband and to materially affect the "pulse-edge" oscillations that appear there, while producing relatively little effect on the forward gain in the amplifier operating band. It is also possible to affect the "loop" passband oscillations, either separately or simultaneously with the π-point oscillations.

An experiment will be carried out on the electron stick where the effect of an external coupler on oscillations and forward gain in a periodic structure will be measured. Provisions will be made for varying the phase velocity of the mode in the external waveguide, the coupling to the waveguide, and the position of the waveguide on the structure. Before this experiment is done, some cold-test work will be done to determine the magnitude and frequency dependence of the coupling that can be achieved between the circuit and the waveguide. Currently, calculations are being carried out to determine the magnitude of the effect of having a nondirective coupling mechanism.

5. Electron Stick (D. K. Winslow,* A. Bahr)

A. OBJECTIVE

The electron stick has been developed to evaluate high-power tube circuits without the construction of a complete tube; it consists of an electron gun, collector, and a long glass tube shielded from the electron beam by a closely spaced tungsten helix. The helix prevents the charging of the glass and is essentially transparent to the rf developed by the circuits which are external to the glass vacuum envelope. Operating at a low duty cycle, nearly 100% beam transmission has been obtained at a peak power of 7 megawatts, 110 kv and 62 amperes. The objective now is to adapt the electron stick to many of its possible uses, namely: to evaluate the effectiveness of the externally coupled waveguides on the centipede circuit in order to eliminate backward wave oscillations; to

*Project supervisor

test the dielectric loaded waveguide as a high-power traveling-wave tube; and to evaluate new circuits, the effects of tapering the circuit, and the effect on tube operation of changing many of the circuit and coupling characteristics. These operations may now be accomplished since the rf circuitry is outside the vacuum envelope.

B. PRESENT STATUS

During previous measurements of the dc characteristics of the electron stick, oscillations were observed between 10 and 100 kv at frequencies of 3.98 kMc and 4.45 kMc, respectively. These are attributed to the backward wave (m = -1) of the helix. These oscillations were eliminated with a lossy material external to the glass envelope. The loss of this material (Eccosorb, LS22) was measured to be 6 to 10 db per inch. With the attenuator in position, two inches of the stick could be without external loss before oscillations could be observed. Two methods of eliminating oscillations are currently being investigated. In the first, an additional helix of attenuator (Karma) wire is wound on the outside of the glass envelope and the insertion loss is measured for different wire diameters and pitch. The second involves periodically loading the electron stick with attenuator rings of higher loss material. These cylinders (about 0.150 in. long) can be used with a structure such as the modified centipede structure which is to be used to evaluate the backward coupling schemes described in the centipede section of this report. These rings, if necessary, will be placed in the field-free region between the relatively shorter gaps of the centipede sections so that the loss is appreciable for only the rf fields of the helix. Measurements on the helix like the one used in the electron stick are continuing in order to determine the amount of attenuation that can be obtained by the coupled helix attenuator. This type of attenuator should be particularly useful since it could be used in any of the contemplated rf structures.

One electron stick is ready for final assembly and bakeout. Most of the components for the second stick are available. The mechanism which is to be used to move the circuit and focusing coils relative to the electron stick has been designed and construction is under way. The motions and guides provided will allow the coils to be removed from the circuit and then reutrned to their original position. This will allow the circuit to be charged with relative ease. Also, the circuit can be removed

from the stick and coils in a similar manner. During the next period, the electron stick and the positioning apparatus should be ready for use.

6. Hollow Beam Guns (K. J. Harker)

A. OBJECTIVE

The purpose of this project is to produce electron guns with high preveance and convergence. The most promising approaches to this problem are based on curvilinear flows instead of the more conventional rectilinear flows. For some time, the principal method of attack on the curvilinear flow problem has been that of experimental cut-and-try techniques. The goal here has been to reduce gun design for curvilinear flow to a more analythical and systematic scheme.

B. PRESENT STATUS

Over the last six-month period our efforts have been mainly concerned with two main areas. One is the continuation of the work on a general method for obtaining solutions to the equations of space-charge limited flow. The other is the development of a high-precision method of calculation to be used as an alternate to the method of analytic continuation for obtaining gun designs.

General Solution to the Equation of Space-charge Flow

In previous reports we have discussed the development to completion of a general computer program for obtaining solutions to the equations of space-charge limited flow corresponding to any (analytic) choice of cathode shape and cathode current density. Since this program requires 10 minutes on the IBM 7090 per configuration, and since many of these runs are in general necessary in order to find a practical gun configuration, we developed early in the period a supplementary program for evaluating solutions on the beam axis alone. This program had the advantage of giving the principal information about a configuration in a far shorter time than the main program.

During this period several new modes of attack were developed which we are now actively pursuing. As mentioned in previous reports, the range of a solution is mainly determined by the position of the critical points in the complex plane of the cathode. No solution exists around such points,

and it is therefore important to seek cases where these singularities are either removed as far away as possible or they do not exist. It is our proposal that cathode shapes which lead to the situation be obtained in the following fashion. In the axially symmetric case the cathode shape can be described in a meridian plane by the polar coordinates [$r(\theta)$ and θ] . Singularities occur wherever

$$\left|\frac{ds}{d\theta}\right| = 0 \quad , \tag{1}$$

where s is the arc length. It is clear that

$$\left(\frac{ds}{d\theta}\right)^2 = \left(\frac{dr}{d\theta}\right)^2 + r^2 \quad , \tag{2}$$

and if we let

$$\left(\frac{ds}{d\theta}\right)^2 = e^{F(\theta)} \quad , \tag{3}$$

where $F(\theta)$ is a polynomial in even powers of θ , then Eq. (1) is never satisfied (except at infinity) and we have the sought-for cathode shape. This shape is obtained by solving the differential equation

$$\left(\frac{dr}{d\theta}\right)^2 + r^2 = e^{F(\theta)} \quad . \tag{4}$$

Although we solved the problem of obtaining space-charge flows with great generality by the general space-charge flow program, we have been hampered until now by not knowing how to use the method of analytic continuation to determine the focusing electrodes.

Recall that in obtaining the general space-charge flow solutions the equations were written in a meridian plane with respect to a coordinate system formed by the electron trajectories and lines of constant transit time. In essence, the method consists of making a certain analytic continuation into the complex domain with respect to the variable labeling the electron trajectories. The original equations, which were unstable, were transformed into a stable form that could be integrated by finite-difference methods. The results of this calculation up to this point do not yield the proper information required for applying our standard method

for finding the electrodes. This additional data must be found by making a further analytic continuation with respect to the transit time. We have recently determined how to do this and will report the details in a forthcoming report.

High Precision Methods

The second phase of our efforts has gone toward the development of a high precision method for gun design purposes. This is an alternate method to that of analytic continuation in which the instability problem is met by carrying many significant figures in the calculation. Although the error grows rapidly, enough significant figures are carried so that at the point of interest enough of them are left to give the desired accuracy. Our first step consisted in proving rigorously that the solution obtained by this method converges for the case of the two-dimensional Laplace equation. Next we successfully tested the method for some simple case of the same equation on a digital computer. At the present time we are applying the method to the determination of the electrodes for an axially symmetric electron gun.

Our experience with this method has led us to the conclusion that it is inferior to the method of analytic continuation. We have observed that it is not particularly fast, that it is very awkward to program on a computer, and that it does not readily give information as to the presence of singularities in the solution. Since our main interest in the high precision method was in applying it to the determination of the electrodes for the general space-charge flow solutions, and since we have now found how to obtain these same electrodes by the method of analytic continuation, it is our plan to abandon this phase of the work as soon as our present efforts come to a logical stopping point.

Future Plans

Our general plan now is to solve Eq. (4) for various cases until a cathode is found of suitable shape with no singularities. A course survey of flows corresponding to promising shapes will be conducted with the on-axis space-charge flow program. Cases with high perveance and convergence will be studied in finer detail with the general space-charge flow program. Finally, the electrodes to produce the flow will be

determined by making the second analytic continuation and then processing the boundary data with our standard electrode design program.

7. <u>Extended-Interaction Klystrons</u> (M. Chodorow,* B. Kulke)

A. OBJECTIVE

The objective of this project is the characterization of planar, stub-supported, ladder-line configurations for use in a high-power S-band traveling-wave tube or klystron, and the building of such a tube. A planar slow-wave structure, in conjunction with a strip beam, can in theory produce more efficient beam-circuit interaction than a cylindrical structure because more of the electromagnetic energy stored becomes available to modulate the beam.

B. PRESENT STATUS

The dispersion behavior of the crankshaft line (C line) shows this circuit to be a hybrid between an interdigital line and a simple meander line, rather than a modification of the stub-supported meander line (SSM line). Calculated interaction impedance exhibits an unexplained (to date) zero in the upper part of the band. Since elsewhere the impedance is of the same order as that of the SSM line, the C line does not appear to have any advantages over the SSM line, though it is considerably more difficult to analyze.

The agreement between measured and theoretical interaction impedance and R_{sh}/Q on the SSM line has been improved (see Fig. 6); an error in the previous interpretation of perturbation data was found and corrected. A discrepancy still exists; some of this is due to the fact that the theory predicts a group velocity which is lower than that measured, over a large part of the band.

For both the SSM line and the C line it was found that all theoretical cutoffs could be closely predicted by simple physical arguments involving resonant bar lengths along the circuit; actual cutoff frequencies estimated from experimental results do not seem to follow these simple predictions, however.

---

*Project supervisor

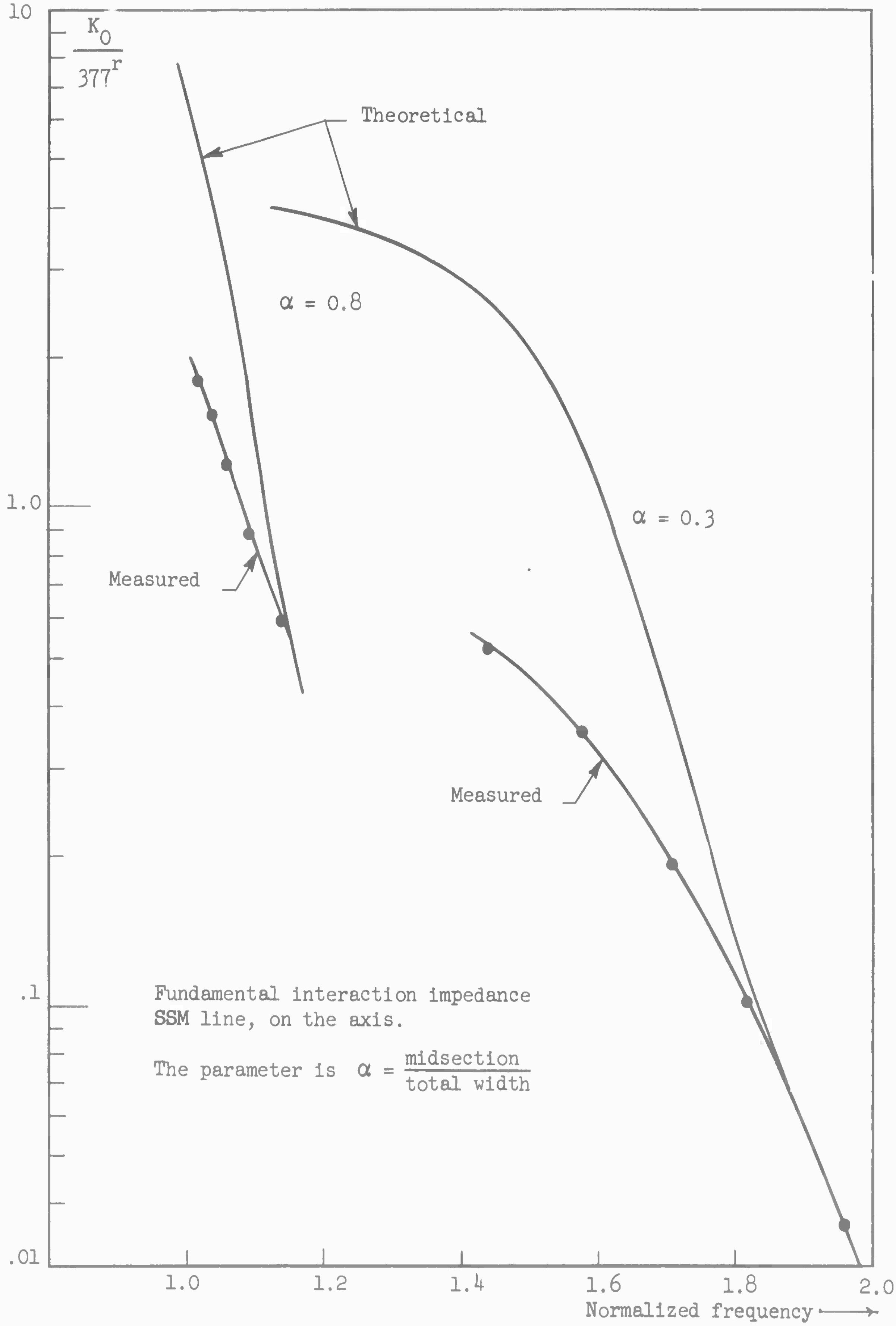

FIG. 6--Measured and theoretical interaction impedance.

An Ash circuit[1] was built and tested for comparison with the SSM line. Because of its greater geometrical simplicity, this circuit has the advantage of a uniquely defined ratio midsection/total width. The SSM line is not as simple in this respect: effective width of the midsection must be determined by "best fit" from the dispersion diagram, e.g., the geometrical mean width of the midsection was increased by about 15% in our case in order to give best agreement with theory. For the Ash circuit, then, measured and calculated dispersion turned out to be nearly identical, at least near midband, for all values of the above width ratio. On the other hand, agreement between measured and calculated impedance was no better for the Ash circuit than for the SSM line.

Our efforts are now centered on evaluating the dependence of SSM line bandwidth on the ratio midsection/total width; on comparing, in normalized notation, the SSM line with its parent connected-ring structure; and on designing well-matched coaxial input and output couplers for the SSM line.

8. Nonperiodic Dielectric-Lined High-Power TWT (A. Karp)

A. OBJECTIVE

The main purpose of this project is to demonstrate the feasibility of a pulsed S-band multi-megawatt 80-100 Kv forward-wave amplifier based on a nonperiodic slow-wave structure. This structure will consist of essentially a copper cylinder uniformly lined with beryllium-oxide dielectric. The immediate objective is to test, at low levels, a nonevacuated structure fitting outside the electron stick (described in section 5) in order to verify that the gain, bandwidth, and freedom from parasitic-oscillation tendencies of the dielectric device are as predicted. A subsidiary aim is to explore the possibilities of such nonperiodic dielectric structures as high-voltage millimeter wave amplifiers or generators.

B. PRESENT STATUS

In order to establish that the elimination of periodicity in a TWT structure, to avoid at the outset the instability problems of conventional structures, can be effected--at least at high beam voltages--with the same, or better gain, bandwidth and power handling capability, we will test

---

[1] E. A. Ash and A. C. Studd, "A Ladder Structure for Millimeter Waves," Trans. IRE, PGED, ED-8, 294-301 (July 1961).

uniform cylinders of isotropic dielectric, in conjunction with the electron stick (see section 5), as the "hot" element. Whether or not the rf guiding dielectric is outside the vacuum, the electron stick principle is very much involved in the project because a beam-dielectric interface may r be left to discharge haphazardly at the required beam density levels. At present, the needed improvements in the electron stick are awaited in the event that modifications will affect the dielectric-guide design.

A development was recently announced, affecting nonperiodic dielectric TWT's in pyrolitically deposited boron nitride. Due to anisotropy, thermal conductivity in one direction may be exceptionally high for a dielectric other than Beryllia. In addition, it may be possible to use the anisotropy in dielectric constant to raise the interaction impedance. Heretofore, this possibility was rejected as an anisotropic dielectric would have had to be made artificially--as with space films of titania--and be unsuitable mechanically.

DISTRIBUTION LIST

	No. of Copies
Signal Corps Liaison Officer RADC (RAOL, Capt Norton) Griffiss AFB, NY	1
AU (AUL) Maxwell AFB, Alabama	1
ASD (ASAPRD) Wright-Patterson AFB, Ohio	1
Chief, Naval Research Lab. ATTN: Code 2021 Washington 25, D. C.	1
Commanding Officer USASRDL ATTN: SIGRA/SL-ADT Ft. Monmouth, N. J.	1
Chief, Bureau of Ships ATTN: Code 312 Main Navy Bldg Washington 25, D.C.	1
AFPR Lockland Br GE Co. P. O. Box 91 Cincinnati 15, Ohio	1
Chief, AF Section MAAG Germany Box 810 APO 80 New York, N. Y.	1
AFSC (SCSE) Andrews AFB Washington 25, D. C.	1
ASTIA (RIPCA) Arlington Hall Station Arlington 12, Virginia	10
European GEEIA Region (ZEM) APO 332 New York, N. Y.	1

	No. of Copies
RCA Laboratories Electronics Research Laboratory Princeton, New Jersey ATTN: E. W. Herold, Director	1
Eitel-McCullough, Inc. San Bruno, California ATTN: Dr. Dunn	1
Litton Industries 690 Industrial Road San Carlos, California ATTN: W. Watson	1
Varian Associates 611 Hansen Way Palo Alto, California ATTN: T. Moreno	1
Telefunken, Ulm, Germany ATTN: Dr. Dahlke	1
Siemens Company Munich, Germany ATTN: Dr. Katz	1
Brown Boveri Baden, Switzerland ATTN: Dr. Luedi	1
CSF Corberville, Paris, France ATTN: Dr. Doehler	1
NDRE Bergen, Norway ATTN: Kjell Bløtekjaer	1
Sperry Gyroscope Company Electronics Tube Division Great Neck, L.I., New York ATTN: Mr. Tom Sage	1
Raytheon Manufacturing Company Spencer Laboratory Microwave and Power Tube Division Burlington, Massachusetts ATTN: Mr. J. Lind	1

	No. of Copies
Raytheon Manufacturing Company Spencer Laboratory Microwave and Power Tube Division Burlington, Massachusetts ATTN: Mr. J. Lind	1
Applied Radiation Company Walnut Creek, California ATTN: Mr. R. Raimonde	1
Hughes Aircraft Corporation Florence and Teale Avenue Culver City, California ATTN: Carl Buczek	1
CERN Service d'Information Scientifique Geneva 23, Switzerland ATTN: Mme L. Goldschmidt-Clermont	1
Chalmers Institute of Technology Gothenburg, Sweden ATTN: Dr. Rydbeck	1
Royal Institute of Technology Stockholm, Sweden ATTN: Dr. Agdur	1
Institute for Defense Analysis Research and Engineering Support Division 1825 Connecticut Avenue, N.W. Washington 9, D.C. ATTN: Technical Information Office	1
Cornell University School of Electrical Engineering Ithaca, New York ATTN: Professor G. C. Dalman	1
RADC (RALTP/LT Schneider) Griffiss AFB New York ATTN: W. Veith	1
RCA, Electronic Tube Division Lancaster, Pennsylvania ATTN: Mr. R. Raimonde	1